Neutralized Drift Compression Experiment (NDCX) - II

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OFES Project Manager: Dave Goodwin

Quarterly Progress Report
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Recovery Act Project:	High Energy Density Laboratory Plasma -Neutralized Drift Compression Experiment (NDCX-II)
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1. Program Overview

LBNL has received American Recovery and Reinvestment Act (ARRA) funding to construct a new accelerator at Lawrence Berkeley National Laboratory (LBNL) to significantly increase the energy on target, which will allow both the Heavy Ion Fusion (HIF) and Warm Dense Matter (WDM) research communities to explore scientific conditions that have not been available in any other device.

For NDCX-II, a new induction linear accelerator (linac) will be constructed at Lawrence Berkeley National Laboratory (LBNL). NDCX-II will produce nano-second long ion beam bunches to hit thin foil targets. The final kinetic energy of the ions arriving at the target varies according to the ion mass. For atomic mass unit of 6 or 7 (Lithium ions), useful kinetic energies range from 1.5 to 5 or more MeV. The expected beam charge in the 1 ns (or shorter) pulse is about 20 nanoCoulombs. The pulse repetition rate will be about once or twice per minute (of course, target considerations will often reduce this rate).

Our approach to building the NDCX-II ion accelerator is to make use of the available induction modules and 200 kV pulsers from the retired ATA electron linac at LLNL. Reusing this hardware will maximize the ion energy on target at a minimum cost. Some modification of the cells (e.g., reduce the bore diameter and replace with higher field pulsed solenoids) are needed in order to meet the requirements of this project.

The NDCX-II project will include the following tasks:

(1) Physics design to determine the required ion current density at the ion source, the injector beam optics, the layout of accelerator cells along the beam line, the voltage waveforms for beam acceleration and compression, the solenoid focusing, the neutralized drift compression and the final focus on target.

(2) Engineering design and fabrication of the accelerator components, pulsed power system, diagnostic system, and control and data acquisition system.

(3) Conventional facilities

(4) Installation and integration

The project will be considered completed when the accelerator and pulsed power systems are in place and tested, and we begin beam production and acceleration. The period of performance for this project is July 7, 2009 to Mar 31, 2012, and the total funding, including contingency, is $11.0 M.

2. Summary of Activities in This Quarter

We made significant progress in several areas this quarter. The main task was detailed engineering design and testing related to modifying the ATA induction cells that are the basic building blocks of the machine. NDCX-II will reuse accelerator hardware from the previous ATA experiment at LLNL; the transfer of this hardware from LLNL to LBNL is approaching completion. Modeling calculations and test data obtained from a mock-up magnetic solenoid confirmed that the solenoids' stray magnetic field must be kept away from the induction cores. An improved induction cell design is underway. We have also finalized the accelerator beamline layout and produced a preliminary structural design of the elevated platform for mounting the pulsed power system.

The pulsed power system for the solenoid prototype was designed and the parts ordered for fabrication. The high voltage trigger generator requirements were determined and vendors identified. We have also sent out the request-for-quote for the accelerator control system design. A purchase order was sent to PPPL for the plasma source neutralizer task.

Computer simulations determined the solenoid alignment tolerance to be +/- 0.5 mm in order for the beam to transit the entire accelerator. We have started a magnetic measurement program to ensure the quality of the finished products. To correct for errors, the machine is designed to allow periodic beam sensing and steering, generally at every fourth lattice period. Using computer simulations, the accelerator performance was optimized for various numbers of induction cells and voltage waveforms.

A detailed WBS project plan was produced. We identified the project's risk areas and developed mitigation strategies. A detailed Baseline Plan cost estimate was made, consistent with cost and schedule constraints. A Lehman Review is now scheduled for January 2010. At the end of this quarter, we estimate that the fraction of completion for the NDCX-II project is be about 3%.

3. Technical Progress

3.1 Physics Support

There are two main purposes for physics support in this project: one is to provide guidance and specifications for the construction of the induction linac, and the other is to provide information and methods for beam diagnostics (steering and alignment) as well as acceleration and compression schemes. One of the major challenges is to produce physics designs and operating points that can make best use of the limited project funding, such that the accelerator components (e.g. the induction cells) installed during this project can be used to generate the most useful variety of beams (with regard to, e.g., the final ion kinetic energy, pulse length and total charge at the target).

During this quarter, the physics support group has made significant progress in several areas to move the project ahead, including:

- Developed, using 2D Warp simulations, injector configurations that use Li sources emitting 2.5, 2.0, and 1.0 mA/cm^2. With the reduced emission rate for the last case, a longer initial pulse, and hence greater compression early in the machine, is required. Ongoing experiments suggest than an emission density exceeding 1 mA/cm^2 may be possible, so we believe this range to be conservative.

- Examined, using simulations, the performance of machines with varying numbers of induction cells. In order to preserve a significant cost contingency, the project baseline design will have fewer than the ~30 cells ultimately desired for maximal operating flexibility and the full range of scientifically interesting ion kinetic energies.

- Examined the consequences of misaligned solenoids, with regard to beam offset and "corkscrew" distortions. Establishment of an nominal alignment accuracy with errors in transverse placement of solenoid ends up to 0.5 mm (flat distribution) should allow almost all of the beam ions to transit the accelerator, though on-target brightness is diminished moderately by corkscrew spreading.

- Examined the feasibility of beam "steering" to reduce offset and corkscrew effects; there appears to be little or no benefit in having an (x,y) correction-dipole pair in every cell, so the baseline design now assumes that both centroid sensing and active correction via dipoles take place only in the inter-cell blocks, i.e., in every fourth lattice period.

- Made major improvements to the ASP (Acceleration Schedule Program) simulation code, which is a fast-running 1-D particle-in-cell code used for longitudinal beam dynamics with space charge, coupled with a set of equations describing the evolution of the centroid for each slice of the beam. The improvements include facilities for obtaining the beam initial conditions from the output of 2-D Warp simulations of the injector, and a better algorithm for estimating near-optimal “ear” waveforms that afford beam-end confinement near the front end of the machine.

3.2 Mechanical Design of the Accelerator System

The building blocks of the induction linac are the induction cells. We have acquired more than 40 cells, together with the Blumlein (pulse-forming network) from the previous ATA experiment at LLNL. The process of property transfer from LLNL to LBNL has been completed.

The original ATA cells have dc low-field solenoids embedded within the induction cell housing. Figure 1 is a schematic diagram of the ATA cell. These solenoids must be replaced by high-field (about 2 Tesla) solenoids for focusing ion beams in NDCX-II. Furthermore, due to the high current required to produce high magnetic field, the dissipated power is too high for dc operation and therefore the solenoid must be energized with pulsed power. In order to further limit the required pulsed power to the solenoid, the diameter of the beam pipe (equivalent to the inner diameter of the cell housing) was reduced to allow using a smaller diameter solenoid, but large enough to provide clearance for beam transport. This reduced diameter also serves to reduce the axial extent of the fringing field near the accelerating gaps, thus reducing the beam transit time through the gap and enabling more efficient use of the induction core's Volt-seconds.

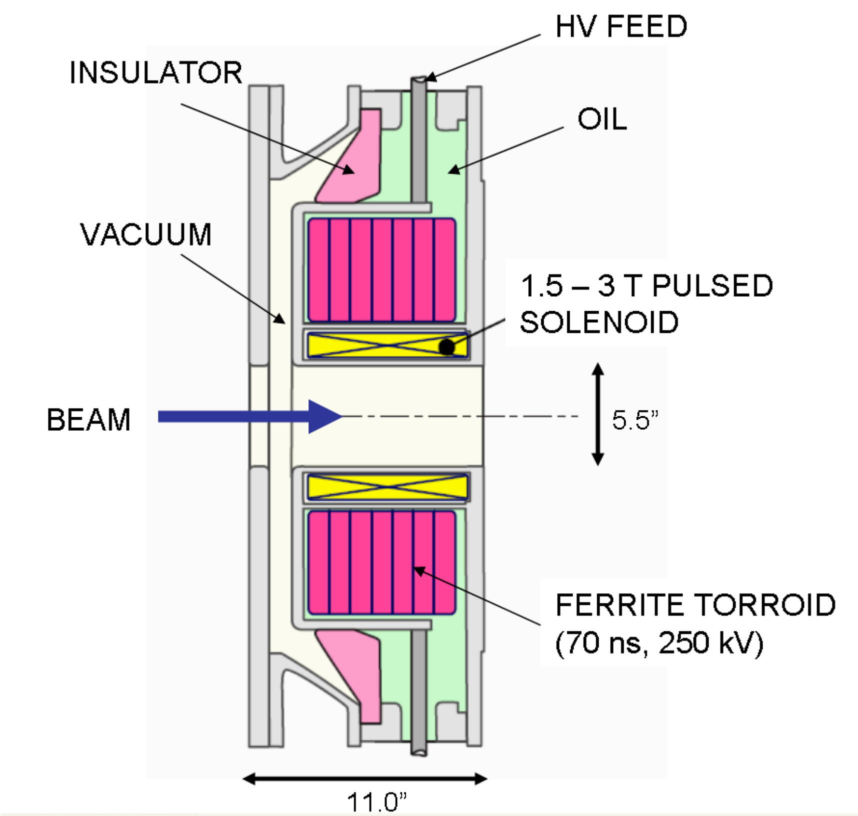

Fig. 1. Schematic diagram of the ATA cell.

We noted another effect of the "pulsed nature" of the strong solenoid field: the induced eddy currents at the end flanges of the cell housing. These currents, if not minimized, would have several adverse impacts. First, they increase the power load on the circuit driving the solenoid. Second, they produce mechanical stress on the flanges, possibly transmitting shocking forces to the main insulator (within each cell). Third, with the superposition of the "reverse" magnetic field generated by the eddy current, more field extends into the region where the ferrite cores are located. This stray magnetic field was found to reduce the available flux swing ("Volt-seconds") of the cores, thus adversely limiting the maximum pulse length of the induction cells.

Two approaches will jointly mitigate the eddy current problem. First, the inner region of each end flange will be modified to reduce its thickness—the increased electrical resistance will reduce the eddy current. Second, a shield will be added outside the solenoid in order to trap the stray magnetic field and keep it away from the ferrite cores. There are several options for this shield: a simple copper pipe with the proper thickness positioned outboard of the solenoid and inboard of the cores; the combination of a ferromagnetic iron pipe and a copper pipe; or a controllable reverse-field "bucking" coil. Recent engineering model calculations (using ANSYS) indicated that the passive method should be adequate. A detailed design of the prototype cell was completed by the end of Sept. 2009.

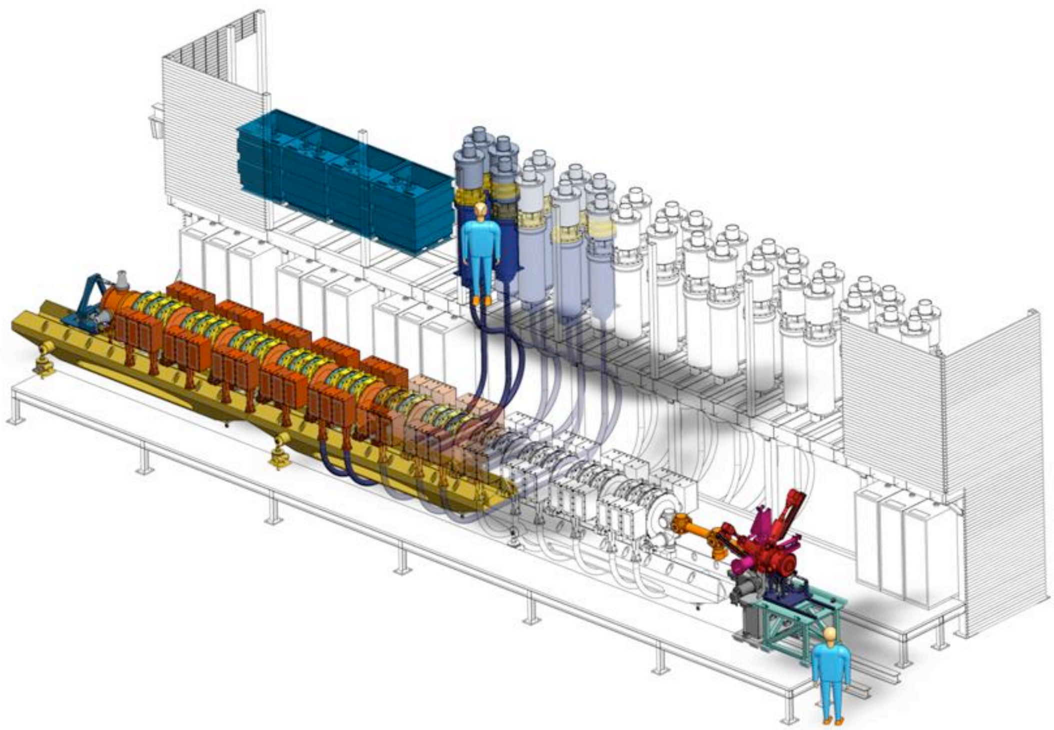

Fig. 2. NDCX-II layout, showing 12 Compression Cells, 3 Accelerator Cells, 5 Diagnostics Cells, 5 Steering Coil Sets, 5 Beam Position Monitors, Injector and Drift Compression. Cost of machine assumes \$8.5M with additional \$2.5M kept in contingency reserve.

We are conducting prototype tests on a test stand that was constructed using the actual ATA parts. The tests will confirm whether the passive method is adequate or not, and if so, whether we need only the copper shield or both the copper and the ferromagnetic shields. The test stand is located at the site of NDCX-II in Building 58 at LBNL, and is currently in operation.

The required modifications of the cell housing, the solenoid, and the magnetic shield are somewhat more extensive than was originally expected before the NDCX-II project start. Their associated cost reduces the number of induction cells that can be fabricated within the fixed project funding. We plan to build enough cells to enable meaningful Warm Dense Matter physics experiments that go well beyond those possible on NDCX-I, and an infrastructure that can readily accommodate additional cells in the future. Depending upon the availability of contingency reserve funds, more cells will be added near the end of the project schedule and the modules appropriately re-arranged for maximal performance and flexibility.

A layout for the NDCX-II facility, as it will appear in bldg 58 at LBNL, was completed. Figure 2 shows the components, the rails, the pulsed power system and the support structures.

3.3 Electrical Designs and Control Systems

The electrical system for NDCX-II consists of several subsystems including:

- High voltage pulsers for the injector
- High voltage pulsed power for the induction cores to compress and accelerate the beam pulse (first stage uses spark gap switched lumped element or transmission line pulsers, second stage uses ATA Blumleins with shaping elements at cells)
- High current pulsed power to the focusing solenoids
- Pulsers to the steering dipoles,
- Pulsers for the plasma source at the neutralized drift compression section.

Amongst these systems, the high voltage pulsed power to the induction cores and the high current pulsed power to the solenoids are the critical ones driving the cost and schedule. We have done preliminary designs, produced cost estimates, and identified available vendors. We produced a floor plan layout with the locations of the various power systems, the cabling, and their support structures.

A test stand has been set up to measure the performance of the ATA induction cells in accordance with the ways they will be used for NDCX-II experiments. The measured waveforms were in agreement with our expectations. More work is needed to custom-shape the waveforms to match that specified by the beam dynamic simulations for compression and acceleration. The high voltage trigger generator requirements were determined and vendors identified. Preliminary noise measurements were made inside the induction cell. This data will be used to evaluate different beam diagnostic designs and maximize the signal to noise ratio.

As mentioned above, the ferrite cores were found to be prematurely saturated by the stray magnetic field from the solenoids, thus confirming the results from modeling calculations. After installing a copper shield to block off the stray field, the measurement will be repeated to determine the required thickness and design of the shield and the required pulsed power to the solenoids in order to produce a 2-Tesla field on axis. The pulsed power system for the solenoid prototype was designed and the parts ordered for fabrication.

The control system is specified to provide digital controls for 200 power supplies, their trigger and timing, as wells as up to 300 channels for data acquisition. The will also be a safety interlock system using 100 status monitors. Specifications have been written up and sent to vendors as part of the process in requisition for bids.

3.4 Conventional Facilities and Safety

The NDCX-II accelerator installation requires adjustments to existing LBNL building infrastructure hardware in the following three areas:

1. Electrical AC power distribution: Additional AC power distribution lines and panels must be designed and installed in order to meet the NDCX-II electrical power needs.
2. Building structural system: A mezzanine structure must be built in order to house the NDCX-II pulsed power system.
3. Building life safety and fire safety: Building code compliance of the NDCX-II accelerator installation has to be evaluated.

During the last quarter, we have made progress in the following areas accordingly:

1. Electrical AC power distribution: We have completed a contract with an engineering company to monitor building power usage over a period of a month. We are now able to evaluate leftover capacity of the existing building electrical sub-station. In addition, we have issued a conceptual design contract to an engineering company for designing any supplementary electrical power distribution system.
2. Building structural system: We have finished a conceptual design contract for the NDCX-II mezzanine structure. We have received conceptual design drawings, structural calculations, and a conceptual cost estimate. Based on the conceptual design, we will initiate a final design contract in October. We are currently planning to build the mezzanine structure in late spring 2010.
3. Building life safety and fire safety: We have organized a building walk-through with the LBNL fire marshal and have evaluated any fire safety implications of the NDCX-II installation. No major additional building work is currently anticipated in that area. In addition, we have contacted a building code consulting company to provide a cost estimate for evaluating any California building code compliance issues of the NDCX-II installation. We are currently evaluating their cost proposal.

4. Key Issues

Impact type: T/B/S <u>means</u> **T**echnical, **B**udget and/or **S**chedule;
Severity Color Code: R=Project likely at risk, Y= Milestones/Deliverables likely at risk, G=Milestones/Deliverables slightly at risk, B=Issue resolved.

	Issues	Response	T/B/S	Impact
1	*Work scope adjustment to meet budget envelope*	*CLOSED – Reduce the number of induction cells and associated cost to allow for ~ 30% contingency reserve*	*T,B*	*Reduce final kinetic energy and beam charge*
2	*Stray magnetic field prematurely saturates the ferrite cores*	*Add copper and/or ferromagnetic shielding in the cell design and perform prototype test*	*T,B, S*	*If uncorrected would reduce the usable volt-seconds & thus accelerator capability*
3	*Beam steering correction*	*CLOSED – Simulation confirmed that making correction every 4th cell is sufficient, thus defines the size of each cell block.*	*T,B*	*Eliminate cost of installing steering in each cell*
4	*Ion source current density affecting injector design*	*Continue to develop the Lithium ion source and confirm the emission current density of > 1 mA/cm^2*	*T,B*	*Injector cost, and final beam charge on target*
5	*Utility power available to the building*	*Hired vendor to survey the utility power availability and the nominal power consumption currently used in the building*	*B*	*require a new power substation to the building*

5. Planned Activities for the Next Quarter

1. Optimize physics design and use of ATA cells as the uncertainty in the need for contingency funds diminishes
2. Complete detailed engineering design of the induction cell solenoid and magnet shielding.
3. Complete detailed engineering design of the dipole magnet in between cell blocks for beam steering
4. Conduct preliminary injector design
5. Complete detailed engineering design of the magnet pulsers
6. Complete the preliminary design of the custom cell pulsers
7. Continue to generate cell voltage waveforms on the test stand that are used in the physics design
8. Complete the requirements document for the control and data acquisition system
9. Quarterly review by NDCX-II Project Advisory Committee

6. Project Management

6.1 WBS

A detailed (level 4) work breakdown structure (WBS) has been established for the project baseline. Estimates of costs by major WBS tasks are shown in Table 1.

	Budgeted Total Cost	Labor	Material	Subcontract
NDCX-II TOTAL	**$8,856,513**	$2,763,933	$4,895,001	$1,197,579
1.0 ACCELERATOR HARDWARE	**$1,965,896**	$944,690	$1,021,206	$0
2.0 ACCELERATOR PULSED POWER	**$2,254,127**	$487,124	$1,767,004	$0
3.0 DRIFT COMPRESSION & FINAL FOCUS	**$292,968**	$0	$0	$292,968
4.0 SUPPORT AND ALIGNMENT	**$506,857**	$202,781	$304,075	$0
5.0 MECHANICAL UTILITIES	**$177,094**	$0	$177,094	$0
6.0 ELECTRICAL UTILITIES	**$136,863**	$46,899	$89,964	$0
7.0 DATA ACQUISITION & CONTROL SYSTEMS	**$874,591**	$120,685	$753,906	$0
8.0 FACILITIES	**$681,651**	$90,880	$590,771	$0
9.0 PHYSICS SUPPORT AND R&D	**$904,611**	$0	$0	$904,611
10.0 INTEGRATION	**$0**	$0	$0	$0
11.0 PROJECT MANAGEMENT	**$1,061,855**	$870,874	$190,982	$0
CONTINGENCY (24.2%) RESERVE	**$2,143,487**			
TOTAL PROJECT COST	**$11,000,000**			

6.2 Project Schedule and Status

The Gantt Chart for the overall project schedule is shown below. At present, the most critical task is the fabrication of the prototype induction cell. We estimated that at the end of this first quarter of the project, we have approximately completed 3% of the total project effort.

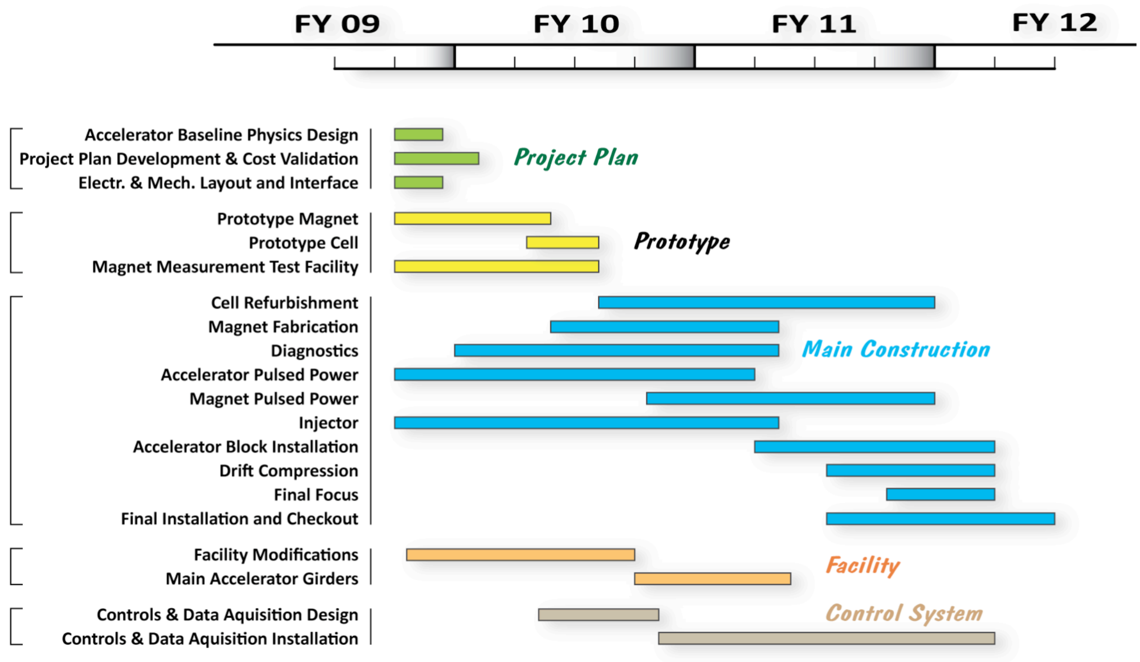

Fig. 3. NDCX-II overall project schedule

6.3 Project Expenditure

The following table shows the total expenditure for NDCX-II during this first quarter of the project:

Jul 09	Aug 09	Sep 09	Total
$81,959	$172,609	$130,916	$385,483

6.4 Milestones

We have fulfilled the 3 milestones for this quarter (according to the NDCX-II Project Operating Plan):

1. CFO releases Recovery Act funding
2. Complete detailed engineering design (of the prototype induction cell)
3. Begin equipment procurement

6.5 Project Review

An informal Advisory Committee of senior accelerator scientists and engineers was invited to a one-day meeting at LBNL on May 27, 2009 (after we have learned that NDCX-II was to be funded as an ARRA project but before the funding was officially released). The members of this committee included experts with detailed knowledge of the ATA machine hardware being reused in the NDCX-II project, and other experts with extensive experience in large scale accelerator development and construction projects. Valuable suggestions were made by the committee providing guidance for the NDCX-II team members to establish work scope, priorities, expectations, and strategies to deal with technical issues.

A Lehman Review that was original scheduled to occur on Oct. 6th, 2009 at LBNL, is now postponed to Jan 13-14, 2010 per DOE/OFES request.

7. Publications and Technical Notes (from this quarter)

7.1 List of Publications and Presentations

W.L. Waldron, L.L. Reginato, and M. Leitner, "NDCX-II Pulsed Power System and Induction Cells", Proceedings of the 17th International Pulsed Power Conference, Washington D.C. (2009).

W.L. Waldron, et al., "Plans for Warm Dense Matter and IFE Target Experiments on NDCX-II", Proceedings of the 18th Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, (2008), published in Fusion Science and Technology, vol. 56, pp. 452-455, July 2009.

A. Friedman, J. J. Barnard, R. H. Cohen, D. P. Grote, S. M. Lund, W. M. Sharp, A. Faltens, E. Henestroza, J-Y. Jung, J. W. Kwan, E. P. Lee, M. A. Leitner, B. G. Logan, J.-L. Vay, W. L. Waldron, R. C. Davidson, M. Dorf, E. P. Gilson, I. Kaganovich, "Developing the Physics Design for NDCX-II, a Unique Pulse-compression Ion Accelerator", Proceedings of the 2009 International Computational Accelerator Physics Meeting, August-September 2009, San Francisco.

A. Friedman, et al., "Physics Design for the NDCX-II, A Short-pulse Ion Beam Driver for Near-term WDM and Target Physics Studies," selected oral presentation, IFSA 2009, San Francisco, September 2009.

M. Leitner, F. Bieniosek, J. Kwan, G. Logan, W. Waldron, J.J. Barnard, A. Friedman, B. Sharp, E. Gilson, R. Davidson: "**NDCX-II, A New Induction Linear Accelerator For Warm Dense Matter Research", Proceedings of the 11th International Conference on Heavy Ion Accelerator Technology, Italy, 8-12 June 2009, to be published on JACoW, the Joint**

Accelerator Conference Website for the Asian, European and American Particle Accelerator Conferences (http://www.jacow.org)

7.2 List of Technical Notes

NDCX2-TN00002	M. Leitner	ATA/LLNL Drawing Package, as of May 2009
NDCX2-TN00003	M. Leitner	ATA/LLNL Drawing Package, as of September 2009
NDCX2-TN00005	JY Jung	NDCX-II Test Solenoid Parameters and Heat Transfer Calculations
NDCX2-TN00006	JY Jung	Cell Prototype Baseline Definition